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Partial Support of Joint USGS-CALTECH Southern California Seismic Network

USGS Award No. G15AC00023

INVESTIGATIONS

This Cooperative Agreement provides partial support for the joint USGS-Caltech Southern California Seismic Network (SCSN) and the Southern California Earthquake Data Center (SCEDC). The purpose is to record and analyze data from earthquakes (including local and regional earthquakes and quarry blasts) during the reporting period. We also generated a database of parametric data and digital seismograms. The primary product derived from the database is a joint USGS-Caltech catalog of earthquakes in the southern California region and the associated waveforms. We maintain the SCSN and SCEDC infrastructures. We also provide rapid response to emergency services, the media, and public inquiries about earthquakes and data for seismological research. All aspects of the operation of the SCSN are carried out in partnership with the USGS Pasadena Office.

RESULTS

Summary of Network Operations

The SCSN operation of network infrastructure consists of: 1) operating computer and communications hardware/software and other instrumentation for data acquisition at the central site and in Amazon Web Services (AWS) sites; 2) installation and field maintenance of new and existing digital stations; and 3) population and maintenance of earthquake databases. Caltech and USGS personnel share these operations responsibilities. Because the SCSN is a cooperative project of Caltech and USGS, all the facilities listed below are jointly operated and contribute to the overall project mission. Current description of CISN and SCSN operations is provided by Hellweg et al. (2020).

At present we operate ~434 seismic stations, and record continuous data from another ~149 seismic stations operated by partner networks. These stations are classified as: 1) broadband and strong motion; 2) short period, 3) strong motion, and 4) event triggered NetQuakes. All of the broadband and strong motion stations have local recording. The broadband and short period stations are free field sites that are located away from structures of two or more stories, and preferentially in places with low ambient ground noise.

Many of the strong motion stations are reference sites that differ from traditional free field sites. They are located close to structures of two or more stories or are located near major facilities or near groups of significant structures. We also record data from three University of California borehole strong motion stations located on UC campuses, and four SCEC borehole strong motion stations. The real-time sharing of strong motion data facilitates multiple use of the data, for ground motion measurements, ShakeMap generation, and seismological purposes such as earthquake locations.

State of health. The SCSN state of health is monitored using SeisNetWatch, NAGIOS, cacti, AirVantage Management System (AVMS) and locally written scripts. SeisNetWatch, NAGIOS and cacti can be operated remotely using a regular web browser and field engineers can be notified via paging or email in case problems develop. AVMS is used to upgrade firmware and continuously monitor all our cellular modems and alert if necessary.

Metadata. Full metadata **are available** for all digital stations in the SCSN, are updated within 1 day of any instrument change, and are available now from scedc.caltech.edu or www.iris.edu for a subset of stations. Only partial metadata are available for discontinued short-period analog stations.

The Station Information System (SIS) is a good example of how the seismic network community has benefited from SCSN/SCEDC development. Initially, SIS was developed as a local metadata database and at the request of the USGS/ANSS is now been made available to the community as ANSS/SIS.

Data Management Practices

Describe briefly your state of progress toward meeting ANSS data management performance standards (standards 4.1, 4.2, 4.3, 5.1 and 5.2).
Hutton et al (2010) describe how the SCSN catalog (1932 to present) is generated and curated.

We meet and in some cases exceed the ANSS standards:

4.1 – Waveforms are shipped via earthworm or Seedlink within seconds to partner networks.
4.2 – We export amplitudes in near real time to CISN partner networks.
4.3 – Phase picks are shipped via earthworm within seconds to partner networks, including NEIC, NCSS and PTWC.
5.1 – We currently have event-based waveforms available within minutes from origin time. Continuous data are archived in near real time, within seconds of acquisition in Continuous Waveform Buffer (CWB).
5.2 – An event bulletin is available within 2 minutes of the origin time of an event. Updates to the catalog are made available within 4-8 seconds of the update to an event.

The timeliness for importing SCSN data into an ANSS archive:

Earthquake parameter data are available within minutes after being processed by the SCSN RT system. All types of earthquake locations are sent to NEIC. For analyzed solutions, there is no lower magnitude threshold. Both automated and analyzed solutions have a geographic constraint (SCSN reporting region).

Event waveform data are available for distribution at SCEDC within 7 minutes. All SCSN continuous waveform data are archived using the CWB system and are available for distribution within seconds of acquisition. Also, see SCEDC report on page 18.

Progress on ANSS Integration

Most of the SCSN partnerships and coordination are done through the California Integrated Seismic Network (CISN). We have regular Program Management Group (PMG) and CISN Standards Group calls.

The SCSN imports real-time waveform data from about 149 partner network stations. We export real-time waveforms to NCSN, BDSN, ANZA, UNR, Earthscope/USArray, CGS, and others.

We view NEIC as our primary backup partner. Two export servers feed near real-time parametric and catalog data to NEIC since 2010. For ShakeMap backup, we work with CISN partners. We have distributed our ShakeMap generation parameters to UC Berkeley and California Geological Survey (CGS) to facilitate backup generation of ShakeMap. The California Geological Survey (CGS) is now the official backup for California ShakeMap.

Our in-house computer facilities at Caltech and USGS Pasadena Office were upgraded in 2011, which included implementation of the hot-isle/cold-isle concept. We also installed two power sources in our computer room, UPS/generator backed-up campus power and Pasadena City Power. New transfer switches provide seamless transfer between power sources. This has also significantly improved the robustness of our operations.

For all significant earthquakes (either felt or larger than a regionally adopted threshold magnitude), the SCSN coordinates public response with USGS Pasadena Office, USGS Menlo Park, NEIC, SCEC, and CISN partners as quickly as possible. The SCSN submits ComCat products near real-time to NEIC via PDL. We send waveforms real-time to NCSN and IRIS. We also export ShakeMap amplitudes to CGS and NCSN.

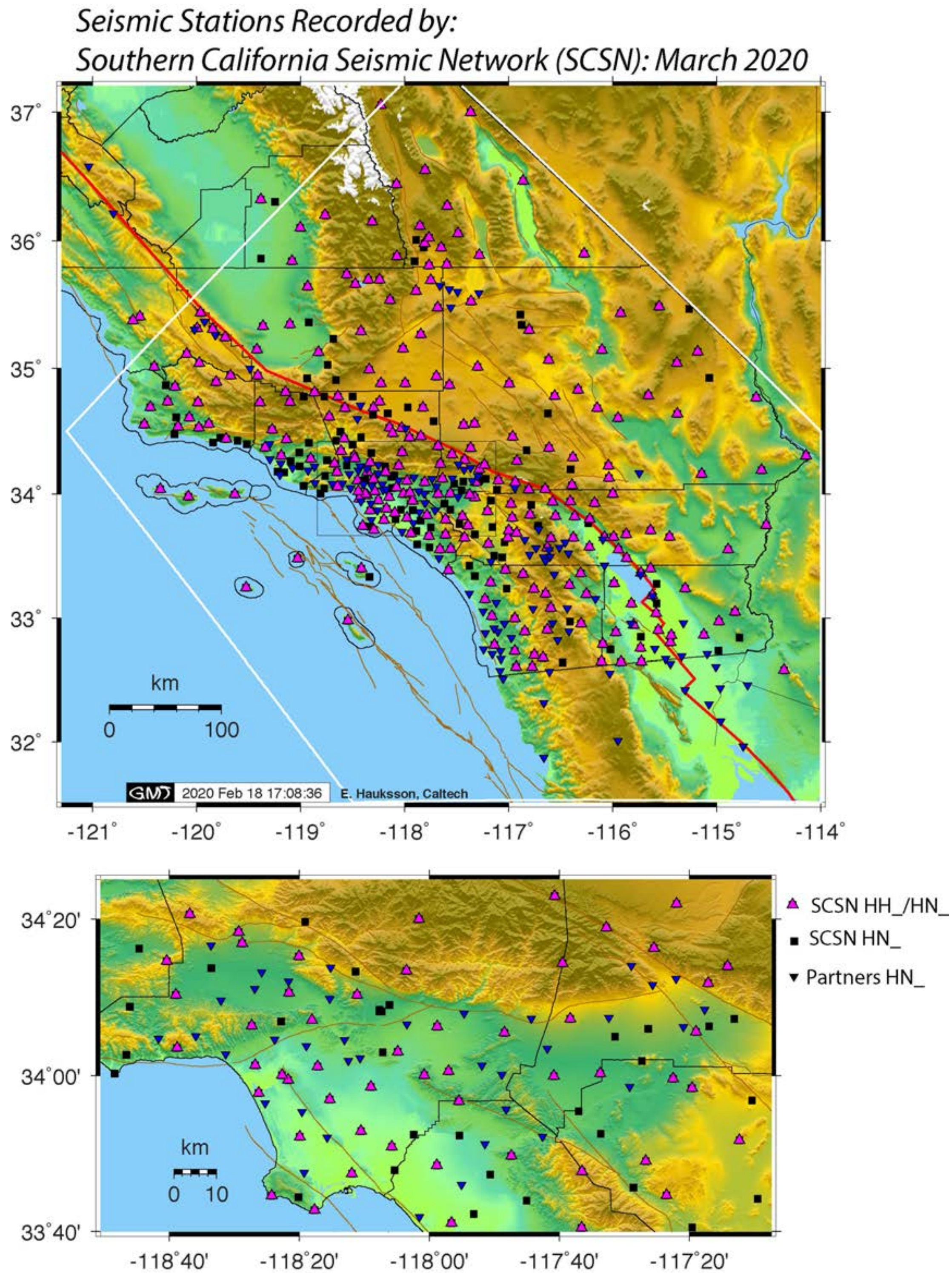


***Figure 1**. Southern California seismic stations recorded and/or operated by the SCSN. SCSN broadband and strong motion stations (HH_/HN_) are labeled with magenta colored triangles. SCSN strong motion stations are indicated by black squares. We have included stations operated by partners, labeled with inverse black triangles (HN_). White polygon outlines the SCSN reporting region for ANSS. The none-real time 73 NetQuake stations operated by the SCSN are not included.*

SUMMARY OF CHANGES IMPLEMENTED IN THIS REPORTING PERIOD

The milestones listed below were completed during the reporting period:

Seismic Stations

- Number of analog stations continues to decrease from 5 to 0 (see Table 1).
- Number of NetQuake stations operated decreased from 84 to 67.
- In 2018 installed/upgraded 10 new stations with Cal OES CEEWs funds (Figure 1).
- Implemented a change needed to exceed the 128 comserv station limit per cs-import machine.
- USGS Microwave Frequency Conversion: Worked with Aviat and USGS to move to new microwave system with minimum impact on data flow from seismic stations.
- Cell Modems: Multiple firmware updates to all devices (150+), password changes, and implementation of TrustedIPs firewall security measure.
- Also assisted USGS Pasadena GPS group with monitoring and upgrades of their devices.
- Regular monitoring of cell modems to check for unauthorized access and compromised cell modems using Sierra Wireless software.
- We operate comserv programs, mserv, datalog and sl2mcast to get data from Basalt dataloggers. This allows us to maintain local wavepools and preserve data quality information previously lost due to the conversion to EarthWorm TraceBuff2 packets.
- We monitor and archive latency for all stations on a real time basis.
- Operation of SIS continues as metadata repository (also see below).
- Implemented numerous improvements to the effectiveness of SeisNetWatch for station health monitoring.
- The first milestone in the collation of site information for the California Geological Survey and the SCSN archive has been completed, with continuously recording stations all documented. Data include site geology description, Vs30 value (shallow S-wave velocity), NEHRP site class, station housing type, station photograph, and a location description. Data are transferred using the strong-motion COSMOS format and are being entered into the SIS database. The aim of the effort is to make all strong-motion data searchable by Vs30, site class, and underlying geology. This work may be extended in future to include stations collecting triggered data.

Real-time Systems Operations

Seismological Algorithms

- Used refined pick_ew parameters based on channel and station sensor type to reduce false triggers.
- Used refined binder configurations to optimize event detection.
- Used refined criteria for event notification to reduce publication of low quality or false events.
- Maintained and used station delays to improve Hypoinverse locations.
- Mw magnitude updates (and moment tensor when available) now sent out automatically within ~4 to 6 minutes for M≥4.0.
- W-phase code running in a research mode to determine near real-time moment tensors.
- Deployed new changes to the AQMS real time system to reduce errors and failures of the Mw magnitude calculation.

Data Export

- We export real-time waveforms to ANZA, ATW, CALVO (USGS), CICESE, DWR, USGS (Menlo), PTWC, IRIS/DMC, UCSB and USARRAY/ANF.
- Most of our real-time waveform export feeds use IRIS seedlink server.
- We export picks and HYP to NEIC, Menlo and PTWC.
- We export waveforms to USGS (CalVO) - We now export 21 stations to the USGS California Volcano Observatory (Menlo) as requested by Dr. Mangan for research projects.

- Setup one temporary seedlink feeds for UNR during a planned conventional test blast.

Hardware Upgrades

- Virtualization - operate two clusters of physical servers to provide virtualization framework in two different computer rooms across the street from each other. Currently we have a total of six servers that use VSphere Essentials Plus software to provide redundancy. Using *VMWare* software we created multiple servers for uses like DRP, Intranet, Build server, Development server and data export servers.
- Using USGS/EEW funds we purchased new computer servers that will strengthen data acquisition for SCSN. Extensive effort was spent in migrating all the real-time AQMS software to x86 Linux servers. We are exclusively using kickstart for installing Linux OS and Puppet for managing configuration parameters to reduce system administration overhead and errors. The systems are currently on-line and in production.
- Added a VMware backup server to regularly archive the VM images from both clusters.
- Our import servers that receive waveform data from other network including ANZA, NCSN, BK, CICESE, DWR are now x86-based Linux servers.
- Import servers handling data flow from SCSN stations use Linux hardware.
- Clustering cs-import servers - enable cs-import servers to work together and provide failover and increased availability.
- Added separate physical network to transport GPS-related multicast traffic.

Product Distribution and System Management

- PDL - We operate PDL on our real-time as well as our post-processing systems and are sending messages to a development PDL server.
- Request tracker - Continued using bug tracking and trouble ticketing system called RT (Request Tracker) for all SCSN stations and telemetry, software development, post processing, system administration and data center issues.
- Configuration management - We are also extensively using software called Puppet and kickstart to deploy new servers and install and maintain standard configurations.

Robustness

- Added connection to seismic station using CalOES PCS microwave. Installed new antenna on top of South Mudd building to keep network separated from Internet.
- Continued with obtaining multiple 4.9Ghz radio licenses from the FCC. This will help improve telemetry and latencies in location with high RF interference like urban areas.
- Operated the gap fetcher program for all Q330 to retrieve data after any telemetry outages.
- We are now using the new SeisNetWatch (SNW) server that uses a database backend to store information. This will allow us to consistently keep track of State of Health (SOH) information for all our stations for a period of six months.
- Changed our real-time systems to acquire redundant data streams directly from the field. We ingest all the redundant data into one ring called RAW_RING and then eliminate duplicates with a program called wftimefilter. All the ‘clean’ seismic data is then fed into a single EW ring called WAVE_RING to make configuration simpler and allow for testing and replay of data and monitor latencies.
- Increased robustness of our Caltech IMSS provided Internet connection by adding two commercial ISP Internet connections and routers.
- We have added redundancy between real-time system and post-processing databases via a private Intranet network connection.
- Self-healing telemetry redundancy - We have increased redundancy of several of our T1 connections by adding cell modem backups that route data during T1 failure.
- With UASI funds, we upgraded the centralized UPS power system in South Mudd in 2014, which provides backup power for all real-time and post-processing servers in the SCSN server room.

- Using NAGIOS (IT infrastructure monitoring software) for monitoring servers and network devices.
- We operate a UASI funded data storage system to hold all log files for our systems, to provide engineering data for troubleshooting and future improvements.
- Pasadena satellite comms. - Continue to operate satellite-based path for sending redundant PDL messages in case of Caltech IMSS Internet connection outage or slowdown.
- OASIS satellite - This is the satellite-based emergency connection between Pasadena and Cal OES in Sacramento. Helped with restoring/testing telephone and network connection via the OASIS satellite.

Improved Network and Server Security

- Use of two-factor authentication for multiple crucial security servers using Duo and yubikeys.
- Run regular scripts to verify all the dataloggers are up to date. Script checks for latest firmware version, and added changes to default usernames, passwords and ssh port numbers.
- Changed default authorization codes, passwords, usernames and ssh port numbers for all Q330 and Basalt dataloggers. Updated and patched software and relevant firmware.
- Deployed regular security patching as these became available.
- All servers use centralized syslog server, which is monitored by Caltech IMSS Network security.
- All servers behind firewall with strict access restrictions.
- Had Caltech IMSS security regularly scan all SCSN servers for vulnerability from on and off campus.
- Installed two VPN routers that will allow us to encrypt all data travelling over the Internet.
- Operate Suricata Intrusion Detection System (IDS) for monitoring and alerting suspicious activities on our private network.
- In the process of documenting standard network security policies for all servers and network devices.

AQMS Improvements

- Documented AQMS-64 build process. Submitted document to CISN Software Working Group (SWG).
- Deployed AQMS-64 on both on-premises and cloud RHEL7 servers.
- Virtualized and upgraded (RHEL7) selected (on-prem) production systems.
- Completed import and multicast all GPS data in support of local development systems.
- Operated AQMS real-time system software to 64-bit Linux OS. Used a redundant encrypted tunnel to get multicast data into AWS cloud for resiliency.
- Operated test and shadow system in AWS cloud with continuous multicast data.
- Maintained policies for using source code SVN repository.

Data Latency

- Assisted with latency archival via an earthworm module at each of the Data Centers on the West Coast.
- Introduced a new latency Data Center location code to specify where the latency is being collected.
- Analyzed the latency performance of all import data for different time intervals.
- Mapped the L1Z values to identify geographic areas with common latency issues (Figure 2). This is done on a regular weekly basis.
- Analyzed latency during the Ridgecrest 2019 events and identified the telemetry issues (Figure 3). Wrote the after-event latency report. The paper describing the SCSN telemetry performance is in preparation.
- Analyzed the latency during the IMSS network outage.
- Operated the tool called the *SCSN scripted SMS station report*, which is sent to a cell phone or via email, latency reported is the mean of the last 5 sec. This tool is used by the engineers in the field. Shared the tool with the UW engineers.
- Use the L1Z data to monitor the short and long term telemetry health (Figure 4).

General

- Updated all Basalts and Obsidians accessible from Caltech with a new Rockhound firmware version 3.16: 77 units total.
- Changed the passwords for all the user accounts and locked unused accounts, changed all the default port numbers to strengthen datalogger security.
- Applied for a Public Safety 4.9GHz radio frequency band and got the application approved.

Seismic Stations as System

- Designed and set up the periodic Basalt dataloggers monitoring tool. The tool checks each accessible datalogger for oddities in the ssh port numbers, open/unlocked user accounts, non-updated passwords, low disk space, problems with USB flash drives, connection problems, firmware and software versions. The report is provided in a searchable pdf and plain text formats. The purpose of the scan is to detect and correct any security and system issues as soon as possible.
- Created and populated configuration data into the Basalt Config Server.
- Analyze periodically the station triggering performance based on the Epic (ShakeAlert EEW algorithm) log files for 15 west coast networks. The results are presented in a text and graphical output.
- Developed the code to calculate the link bandwidth to each datalogger, and obtained the results. Along with latency, this allows us to verify the link improvements.
- Wrote and installed a script on all Basalts to collect the reboot information with a cause of reboots, temperature, and voltage.

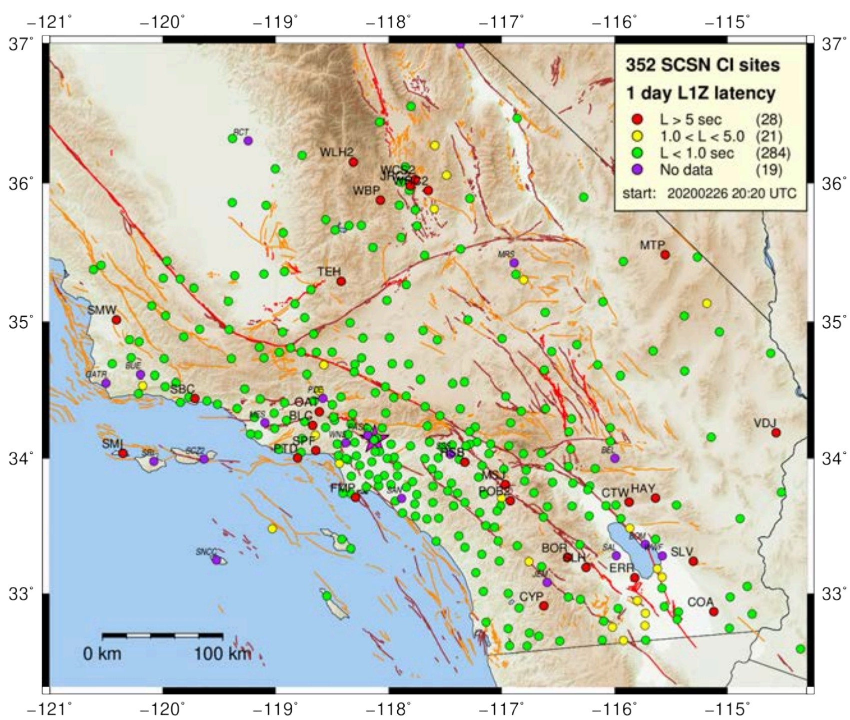


***Figure 2**. Map of SCSN station coverage showing the color-coded latency range values per site.*

Radio Telemetry Project

- Wrote an automatic line of site tool to process the sites in bulk and identified 100+ SCSN sites for connecting to CalOES MW towers.
- Tested Xetawave Xeta9, Cambium N500 and Freewave Zumlink 900MHz radios.
- Worked closely with USGS field engineers on Desert loop telemetry upgrade implementation details.

- Selected and ordered 60 Cambium N500 spread spectrum radios with antennas for connecting to Cal OES towers and SCSN telemetry upgrades.

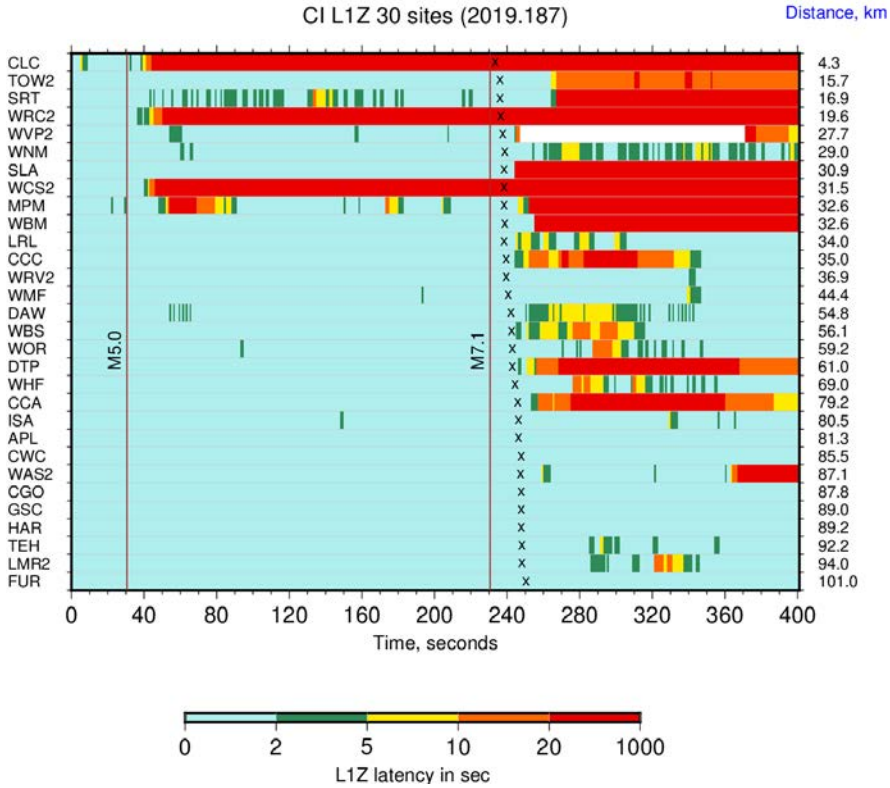


Figure 3. *Station data latency in 1-second increments for stations near the Ridgecrest mainshock. Station distances shown on the right side in km. "x" symbols mark P-wave arrival time. White bar shows a period of no data from L1Z. Only 7 of 20 stations within 80 km maintained timely data delivery for the full ~20 s of active rupture of the M7.1 mainshock. The figure is showing station latency response to an M 5 foreshock 200 seconds before the mainshock as well. Severe latency at three stations continued through the mainshock.*

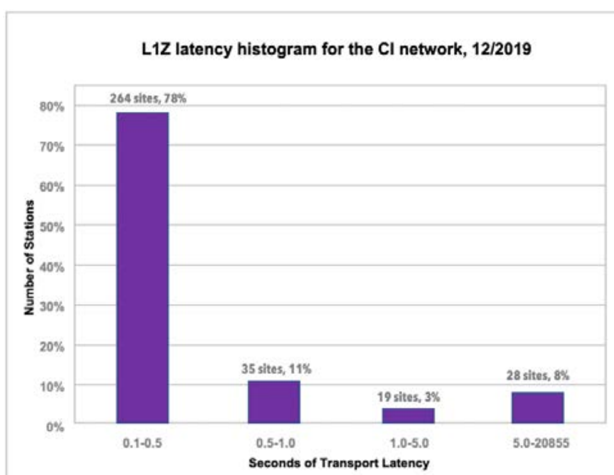


Figure 4. *Transport latency histograms for 2019/12 for the SCSN (CI) stations only. The number of monitored data delivery sites has increased from 272 to 352, which may change as stations go off-line or on-line as they are repaired. The transport latency has improved overall.*

VPN Implementation

We have continued to implement a virtual private network (VPN) that extends between our Internet-based field stations and the data processing center at Caltech in Pasadena. VPNs improve network security, helping to prevent attackers from interfering with our operations. VPNs also allow us to use multiple Internet paths for data collection, with automatic failover and rerouting if one path fails.

In 2018 we made the following improvements:

- We installed MikroTik routers and implemented VPNs at about 12 existing sites with third party hosted/campus Internet connections. About 19 in this category remain to be installed.
- We installed MikroTik routers and implemented VPNs at all 10 of the new CEEWS sites that we installed. These sites are on SCSN-managed cell modem or VSAT Internet connections. We plan to install VPN routers at all new sites we construct in the future.
- We implemented backup VPNs via cell modem with automatic failover at several sites with primary radio or wired network connections: Fort Scotty, plus the three LA County Fire stations mentioned below. Salton Sea Wildlife will also have this completed by the end of 2018.
- Completed a Cal OES pilot project to bring in seismic data over a state microwave link directly to Caltech. One station for now, but plans for more.

In 2019, we made the following VPN improvements:

- Installed new VPN routers and established encrypted telemetry at 9 newly-constructed seismic stations.
- Additionally, installed new VPN routers and established encrypted telemetry at 10 existing seismic stations with third party hosted/campus Internet connections.
- Established a framework for VPNs to extend from seismic stations directly to the Amazon Web Services (AWS) cloud using existing VPN routers at sites, with 3 working prototypes so far. We intend to implement this VPN configuration at 60+ more seismic stations in 2020.
- Implemented backbone VLANs and improved our dynamic routing configurations at Caltech, allowing for more efficient data paths and easier troubleshooting of VPN issues.

Coachella Valley/Salton Sea Telemetry Upgrade ("Desert Loop")

We have upgraded our backbone radio links in the Coachella Valley/Salton Sea area (collectively referred to as the Desert Loop), replacing aging 900MHz radio pairs with new high-throughput 4.9GHz pairs. In parallel with these radio upgrades, we have installed enterprise-grade routers at each key location and have added backup Internet links via cellular modem and satellite.

As of the end of 2019, about 32 individual seismic stations are telemetered via the Desert Loop network. All of these have at least two possible telemetry paths to Caltech, with a dedicated T1 line as primary and with automatic failover to encrypted VPNs via cellular or satellite. In early 2020 we plan to connect the north and south halves of the network together, improving redundancy even more. (see Figure 5)

Pasadena

Completed wavenet connection within the cloud between cs-arctic (data acquisition from the field stations) and arctic (data processing) allowing for collection of all stations with a connection to public network straight into the cloud. This also resolved an issue with collecting data from Basalt/Obsidian/Seedlink Servers, which have a wavenet/multicast interface requirement (as opposed to Q330 which are not dependent on this).

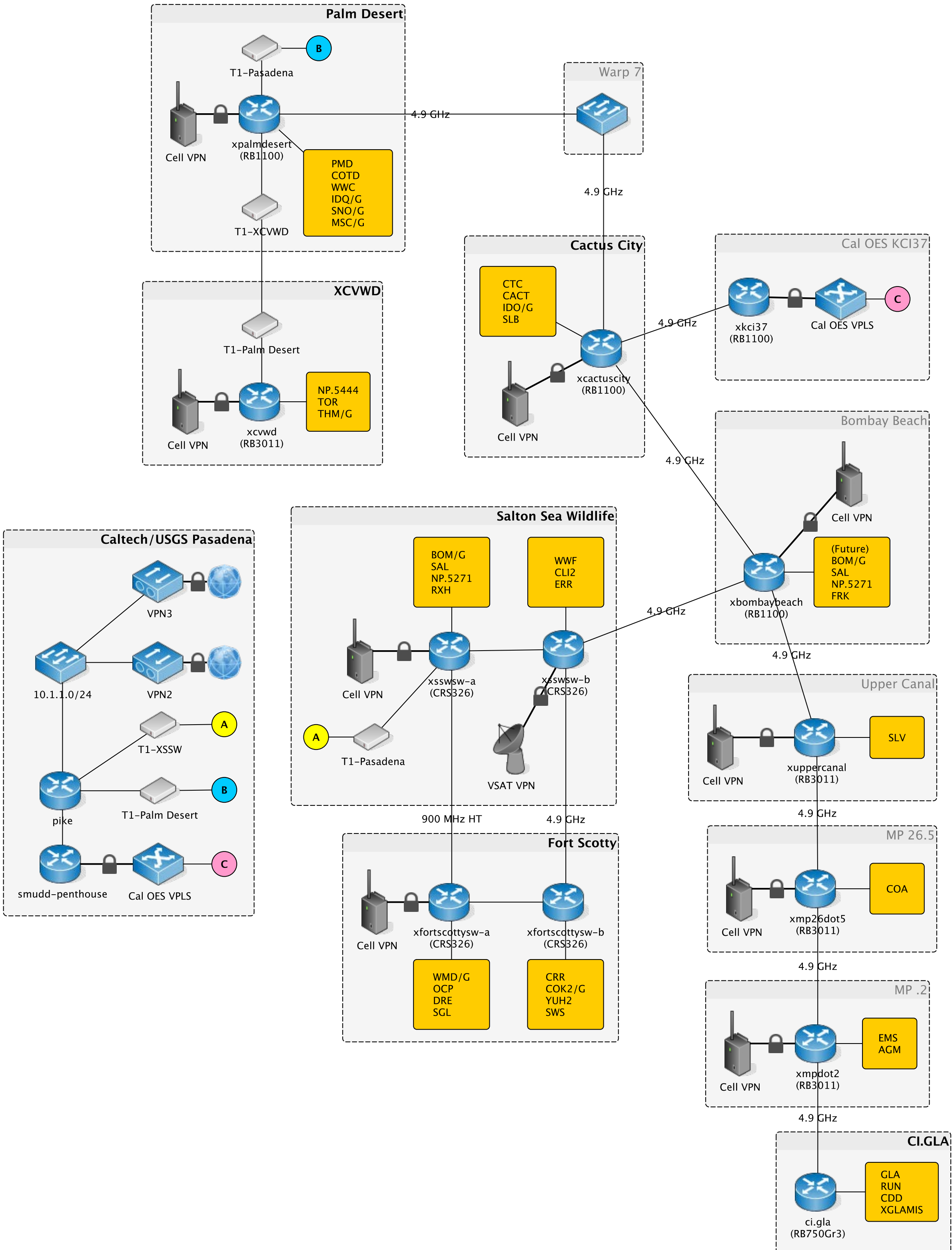


Figure 5. *Schematic diagram of the SCSN Desert Loop radio network in Coachella and Imperial Valleys. This illustrates the needs for design of networking, IP-numbers, and use of radios, cell modems, T1-line etc. to provide reliability and redundancy.*

Amazon Web Services (AWS)
Each field site establishes a single GRE/IPsec tunnel with a cloud-hosted Mikrotik RouterOS installation. We require only a single tunnel because AWS's high-availability network infrastructure will minimize potential outages. An AWS-based cs-import server connects to each site via the Mikrotik cloud router. There will be no failover routing involving AWS and the Pasadena VPN routers – AWS is a separate acquisition strategy for a second data port on the dataloggers.
In order to synchronize seismic data between AWS and our Pasadena data center, we have dedicated an additional pair of routers to establish a VPN tunnel between the two locations. Multicast seismic data will be constantly streamed to AWS to be processed and archived. Data can also be streamed from AWS to Pasadena if needed, but this is not enabled by default in order to reduce transfer fees.

Recent Progress
- Completed the multicast data streaming project with automatic failover.
- Have ~25% of seismic sites streaming data directly from the field to AWS, and more will be added soon.
- Collaborated to create a script able to change the maximum number of seedlink connections allowed to basalt dataloggers *en masse*. Needed for large-scale roll-out of dual feed collection (terrestrial and cloud).
- Troubleshooting of issue where Arctic sees data from both terrestrial and cloud sources. Identified three possible approaches to separate these station feeds (port, wavenet interface, multicast host).
- Prepared overview summary of options with specific configuration aspect examples.
- Explored further the possibility of separation by MulticastHost/multicast address.
- Wavenet Interface separation approach. Established a second wavenet interface on arctic1.
- Developed the VPN tunnel to the second wavenet interface on Arctic to separate cloud and terrestrial feeds. Working on fine details to allow for scalability, not yet complete.
- Successfully tested Port separation approach for direct data shipment using stations CI.AVC (Basalt) and CI.SMR (Q330) to arctic into the WAVE_RING - avoided duplicates (from terrestrial collection) by modifying the port number used.

The data in Table 1 show that the number of stations and channels operated/recorded by the SCSN continues to grow, because of the added EEW funded stations (Figure 1).

Table 1: Seismic Stations Operated and/or Recorded by the SCSN in January 2020

Summary Statistics for Regional/Urban Seismic Network	Number	Station Response Information in dataless SEED volume(s)
Total no. of stations operated and/or recorded	354+)/562	434*)
Total no. of channels recorded	11,448	
No. of short-period (SP) digital stations: op/rec	85**)/179	85
No. of old style analog stations with VCO/Radio	0	0
No. of broadband (BB) stations: op/rec	254/310	256
No. of stations maintained & operated by network	427***)	427
No. of stations maintained & operated as part of ANSS	427	427

+) Does not include triggered NetQuake stations (67).
*) We produce authoritative SEED volumes for CI-network stations; partner networks such as AZ or BK produce their own SEED volumes.
**) Includes installations with strong motion sensor and old analog stations.
***) Includes BB/SM, SM, analog, and triggered NetQuake stations.

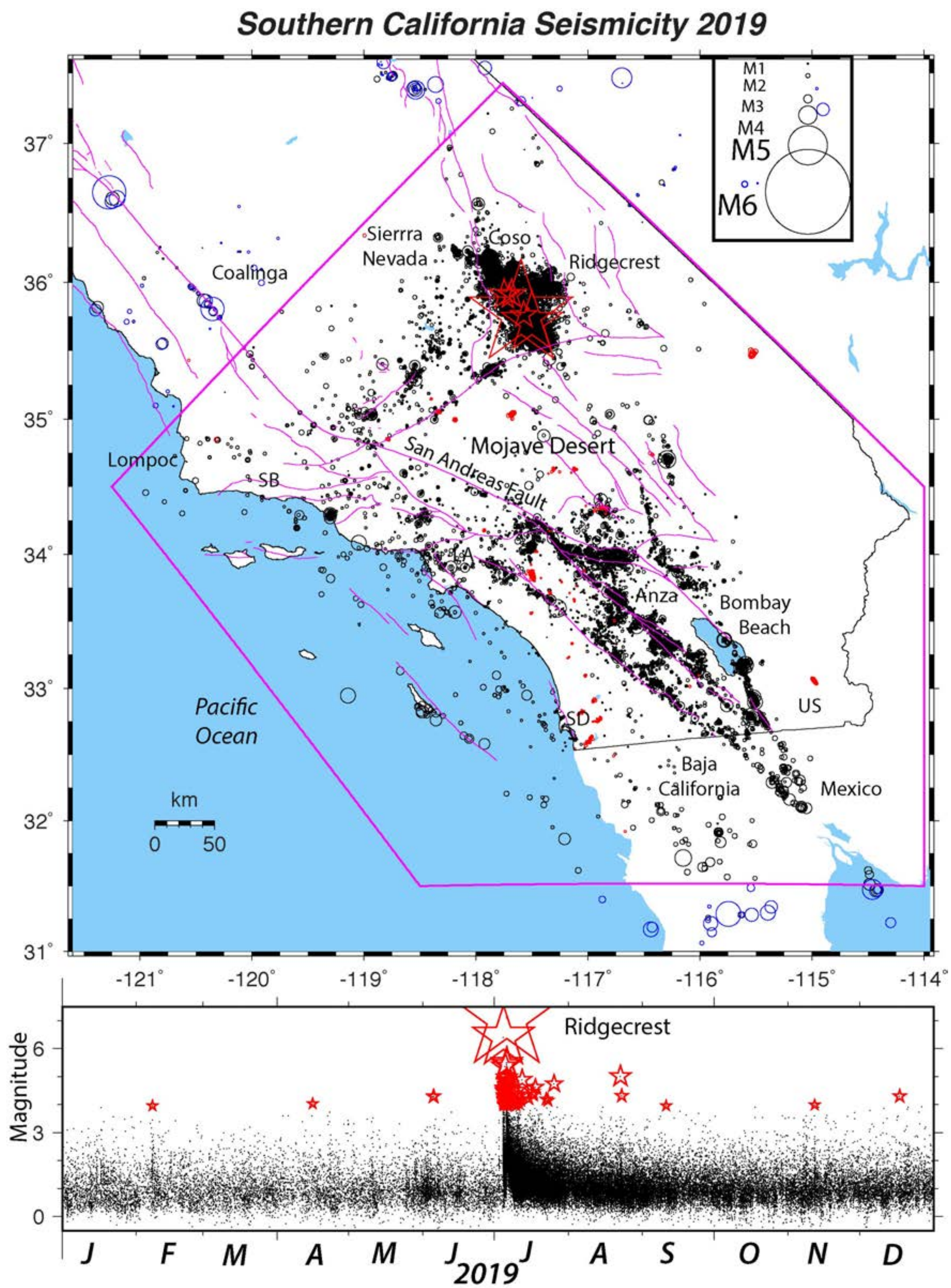


***Figure 6**. Seismicity recorded by SCSN and archived by SCEDC during 2019. The black circles are local earthquakes, red circles are quarry blasts, and blue circles are earthquakes recorded but occurred outside the SCSN reporting region. The SCSN reporting region is within the magenta polygon. The magnitude-date plot of events in the reporting region shows M≥4.0 local earthquakes as red stars. LA – Los Angeles; SB – Santa Barbara; SD – San Diego.*

DATA-POST-PROCESSING

Timing and review of detected earthquakes is up to date for most of the period and reporting region, with the exception of the Ridgecrest sequence. All earthquakes of M≥3 in the Ridgecrest sequence have been timed and reviewed and analysis of smaller magnitude events is ongoing. (For details see below.)

ARCHIVING

For details, see SCEDC report towards the end of the main report.

Table 2: Summary of earthquake magnitude distribution recorded/reported by SCSN

Mag	2015	2016	2017	2018	2019
Total # Events	15,019	14,116	15,710	20,276	60,367
≥2.0	888	1,081	972	1,051	7,214
≥3.0	97	124	114	116	1,218
≥4.0	11	11	4	9	114
>5.0	0	1	0	1	6
≥7.0	0	0	0	0	1
# of ShakeMaps Generated	56	63	60	69	377

Seismicity Summary for Southern California: 1 Jan. 2019 – 31 Dec. 2019

Total number of earthquakes recorded by the SCSN during the period 1 January 2019 to 31 December 2019 for our reporting region: 60,752 (Figures 6 and 7; Table 2). The SCSN also recorded 647 quarry blasts. These earthquakes and quarry blasts, that are located inside and just outside of the SCSN reporting region, occurred at an average rate of 168 events per day during the reporting period (minimum rate 18 per day, maximum rate 2,110 per day). Only a few light earthquakes occurred during the first half of 2019, while the latter half was dominated by the Ridgecrest sequence which included a major mainshock (M7.1) and strong foreshock (M6.4). Data availability is described by Hauksson et al. (2020).

During May and June of 2019, an earthquake swarm in the Fontana/Glen Avon area (near the border of San Bernadino and Riverside counties) caused some public interest and concern, even though the largest events were only minor magnitude. The SCSN recorded daily seismic activity in the swarm starting May 25th, peaking at around 150 events per day on June 2nd and 3rd, and in total over 1,000 events were recorded. The largest earthquake in the swarm was the M3.2 on 2nd June 2019 16:36:36 PDT, and in total 5 earthquakes of M≥3 were recorded, and over 50 earthquakes of M≥2. Events were relatively shallow (1-2 miles) and this may have contributed to community concern and to events being reportedly felt even at smaller magnitudes. Swarms of small magnitude events (M<4.0) are relatively common in the area, extending from Riverside to Chino. The swarm falls within the northeast trending Fontana Seismicity Trend, which has no major mapped fault but relatively abundant small seismicity indicating a local network of small fractures and faults, with activity probably related to the tectonic loading of the nearby San Jacinto and San Andreas faults.

The most notable seismicity within the SCSN region during 2019 is the Ridgecrest Sequence, which started on July 4th, 2019, and included one strong (M6.4, 2019/07/04) and one major (M7.1 2019/07/05) earthquake. As of 31st Dec 2019 the SCSN had recorded over 43,000 aftershocks and analysis of events is ongoing. This activity falls within the eastern California Shear zone (ECSZ), a region of distributed faulting associated with motion across the Pacific:North America plate boundary. The closest large population center is the city of Ridgecrest with a population of 28,000 people. Maximum shaking levels were estimated to be MMI IX (Violent) in the epicentral region and very strong shaking (MMI VII) occurred over a 40 km wide region near the epicenter that includes the city of Ridgecrest. Shaking was widely felt throughout California, including light to moderate ground shaking in Los Angeles, weak shaking in the San Francisco Bay Area, and felt shaking extending at least as far east as Phoenix and as far north as Sacramento.

The 2019 Ridgecrest ruptures, while occurring on previously (mostly) unmapped fault lines, are located in a region well-known for seismic activity. The M6.4 earthquake on July 4th, 2019 appears to have broken across two near-orthogonal faults, predominantly on a NE-SW trending fault with left-lateral strip-slip according to reports of surface rupture. The M7.1 earthquake on July 5th 2019 appears to be in the same fault zone, but the rupture was on the NW-SE fault plane and with a right-lateral strike-slip mechanism. The M7.1 epicenter is located at the NW end of NNW-oriented fault involved in the M6.4 earthquake. The ECSZ has hosted a number of M7+ earthquakes over the last 150 years, including the M7.1 Hector Mine event in 1999 (October 16th), and a number of moderate-sized earthquakes have been recorded in the Ridgecrest area. Over the past 40 years, eight other M5+ earthquakes have occurred within 50 km of the July 2019 earthquake.

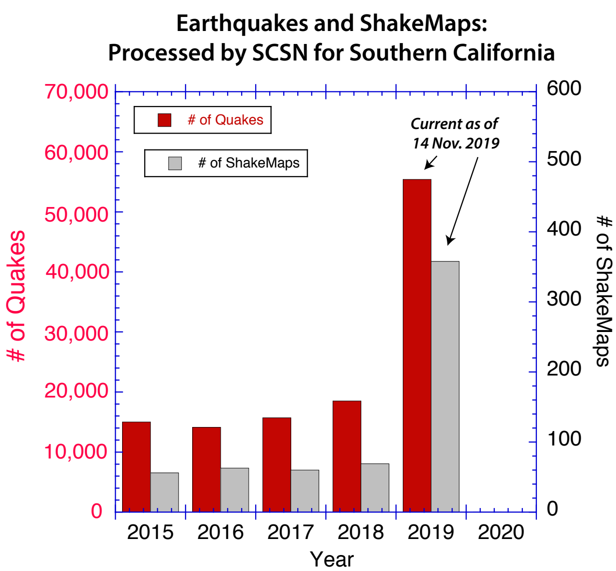


Figure 7. *Number of local earthquakes cataloged and ShakeMaps produced by the SCSN and SCEDC for the last 5 years*.

There was some foreshock activity recorded in this sequence, notably a M4.0 about 30 minutes prior to the M6.4 on July 4th, 2019 (Figure 8). On July 5th there was a M5 three minutes prior to the M7.1. The current aftershock zone extends from the Garlock fault in the south to the southern termination of the 1872 M7.5 Owen's Valley in the north. The majority lie along the NW-SE rupture plane of the M7.1 earthquake, with additional clusters lying approximately 25 km NW from the mainshock about 10 km to the SE of the Coso Geothermal Field, and to the E towards Death Valley. Seismic activity to the north and south in the ECSZ, and at places along the Garlock fault, may be found to be ongoing regional stress adjustment. Ridgecrest aftershocks towards the end of 2019 were continuing at an average rate of about 60 per day. Analysts continue to work on processing events from the sequence, improving both the source parameters and extracting events that weren't automatically detected by the real-time system due to the overwhelming seismic energy in the first hours and days. This effort is expected to be ongoing for 2 years after the event and an extra analyst was hired to assist with the processing. Additional data from a deployment of portable instruments very close to the epicentral region is being episodically added to the archive, leading to additional automatic and manual processing of events throughout the sequence.

Media and public interest was high throughout the sequence, with press briefings held within an hour of each of the strongest two events, ongoing press briefings, twitter and website postings (on www.scsn.org) and numerous interviews with print, radio and TV outlets. The cloud-based websites of both scsn.org and scedc.caltech.edu stood-up well to the intense surges in demand. The sequence is also the focus of many scientific studies and ongoing research.

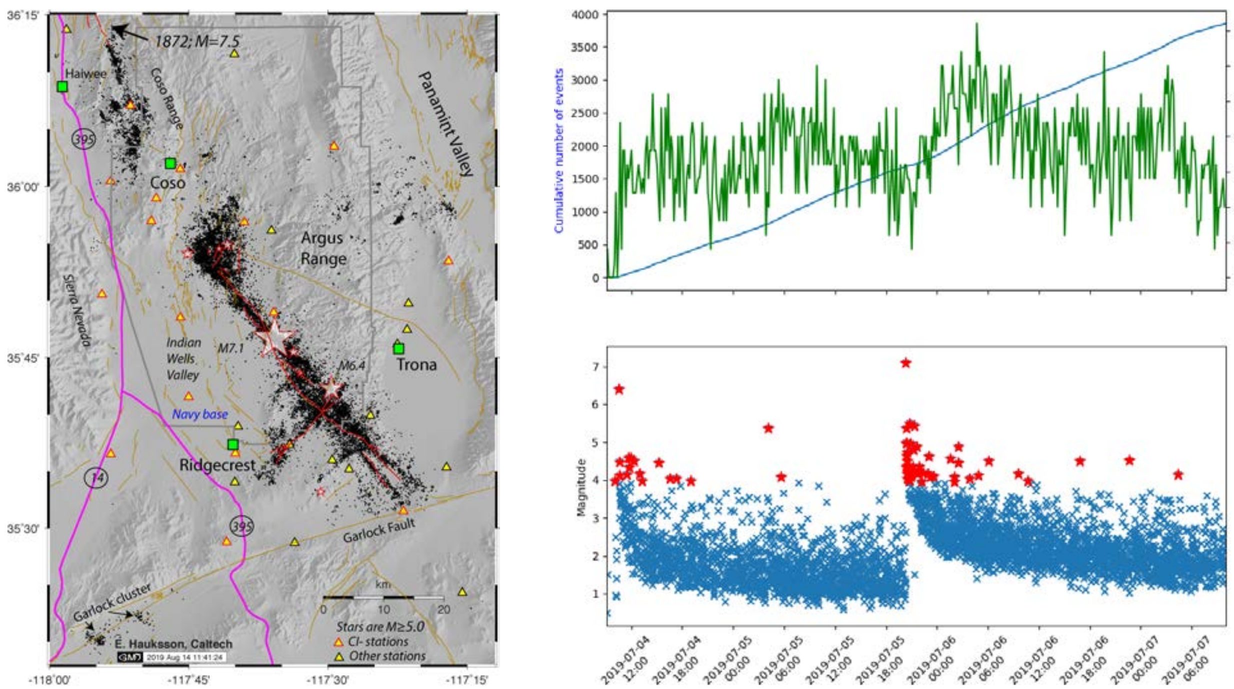


Figure 8. ***(LEFT)*** *The 2019 M6.4 and M7.1 earthquake sequence recorded by the Caltech/USGS Southern California Seismic Network. Black circles represent the aftershocks. The red stars are events of M≥5.0. White lines are previously mapped faults. The new fault scarps are shown in red. Main highways shown in magenta color. The outline of the Navy base is shown in blue. Map showing relocated current events in the Ridgecrest earthquake sequence. Events are shown size-scaled by magnitude.* ***(RIGHT)*** *Time series of the first 3 days of the Ridgecrest earthquake sequence. The upper plot shows the cumulative number of events (blue), as well as the number of earthquakes per 20 minutes (green). The lower plot shows earthquake magnitudes through time, with events of M≥4 marked as red stars.*

Table 3: Earthquakes of M≥4.0 recorded by the SCSN during the reporting period, with the exception that only earthquakes of M≥5.0 are included from the Ridgecrest sequence

#EVID	Mag	Local date	Local time	Lat.	Long.	Dep.	Descriptive location
37523530	4.0	2019/02/07	08:41:24	34 42.2 N	-116 17.2 W	1.6	12km W of Ludlow, CA
38624056	4.3	2019/06/05	03:47:18	32 49.4 N	-118 29.0 W	8.4	13km W of San Clemente Is.
38624424	4.3	2019/06/05	07:32:09	32 50.3 N	-118 30.2 W	8.4	15km W of San Clemente Is.
38443183	6.4	2019/07/04	10:33:49	35 42.3 N	-117 30.2 W	10.5	11km SW of Searles Valley, CA
38450263	5.4	2019/07/05	04:07:53	35 45.6 N	-117 34.5 W	7.0	16km W of Searles Valley, CA
38457487	5.0	2019/07/05	20:16:32	35 43.5 N	-117 33.2 W	0.9	14km WSW of Searles Valley, CA
38457511	7.1	2019/07/05	20:19:53	35 46.2 N	-117 36.0 W	8.0	18km W of Searles Valley, CA
38457687	5.5	2019/07/05	20:47:53	35 54.1 N	-117 45.0 W	5.0	15km ESE of Little Lake, CA
38457703	5.0	2019/07/05	20:50:59	35 54.2 N	-117 42.0 W	8.3	19km E of Little Lake, CA
38457847	5.4	2019/07/05	21:18:55	35 54.6 N	-117 41.1 W	7.4	20km E of Little Lake, CA
38624623	4.2	2019/07/22	09:26:56	33 59.7 N	-116 2.7 W	7.9	16km S of Twentynine Palms, CA
38996632	5.0	2019/08/22	13:49:50	35 54.4 N	-117 42.5 W	2.4	18km E of Little Lake, CA
38824959	4.0	2019/09/10	13:21:49	33 35.6 N	-117 16.2 W	13.7	1km ESE of Wildomar, CA
38238746	4.0	2019/11/11	18:13:52	32 47.5 N	-115 32.8 W	18.5	1km ENE of El Centro, CA

The AQMS systems running at the SCSN performed reliably throughout the Ridgecrest sequence, with minimal variation observed in automated event detection, analysis and distribution even during the periods of highest event rates. Reporting for all significant events met ANSS standards, and requirements of the new large magnitude ANSS policy were met promptly utilizing web interfaces (short-term) and making manual changes in the archive databases (long-term). The SCSN is continuing to provide the highest quality data resource including waveforms, event listings and derived products.

Several ongoing projects aim to improve the value of the authoritative SCSN catalog:

- Incorporation of data from two additional sets of station deployments in the epicentral region, including waveforms and picks where available;
- Use of an externally calculated template-matching catalogue (Ross, Z.E., Trugman, D.T., Hauksson, E., and P.M. Shearer (2019). Searching for Hidden Earthquakes in Southern California. Science.) to extend the SCSN event database and accelerate the review and QC process.

The Southern California Earthquake Data Center

southern california earthquake data center

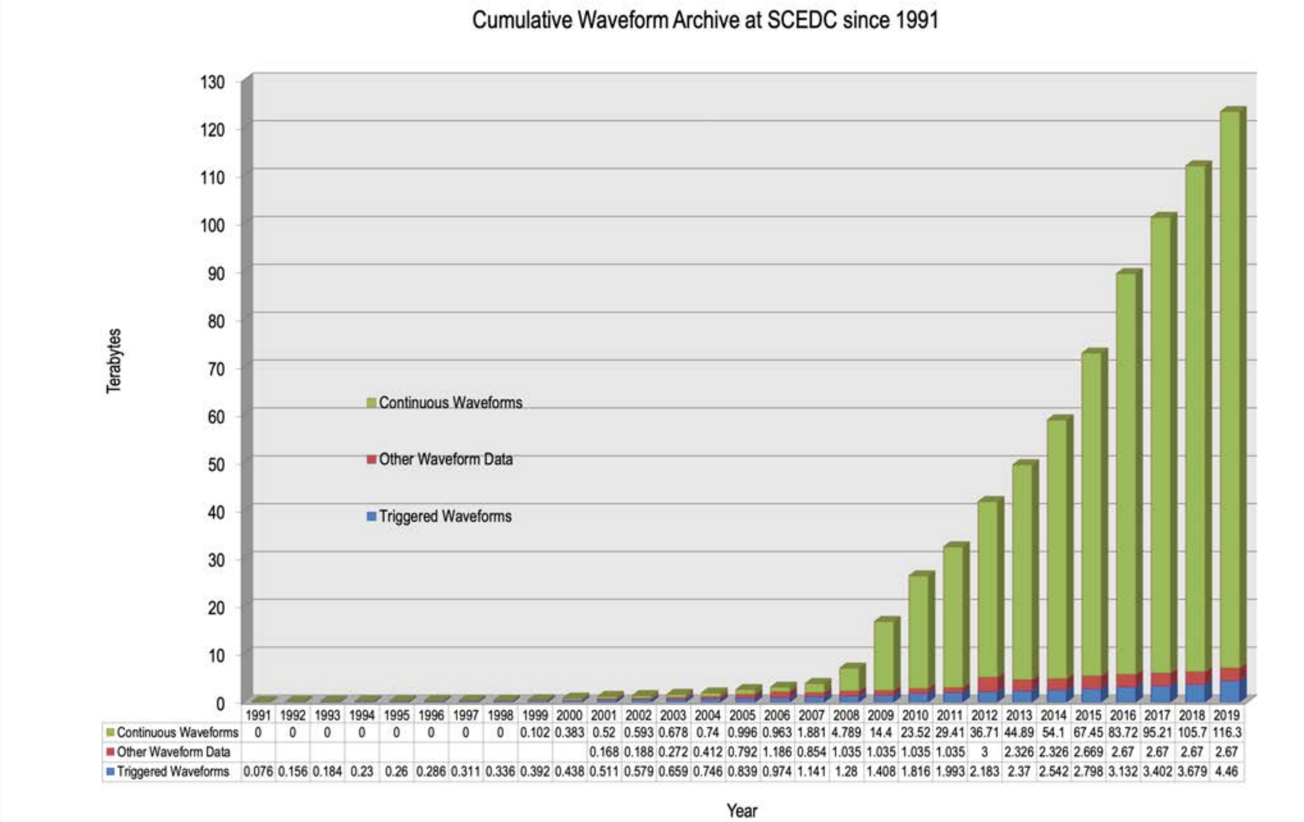
Data Processing and Production of Earthquake Information

We carried out the following activities:

- Continued to archive SCSN waveforms data (Figure 9).
- Loaded aftershock data (ZY network) into archive and ran real-time solutions through automated post processing to refine locations.
- We continue to support our FDSN web services and integrate them with popular frameworks such as ObsPy.
- Implemented a waveform availability service that describes the dates for which waveforms for a given channel are available at the SCEDC. In 2019 we added the query endpoint.
- Provided database support for RSNs using AQMS. Done at the request of ISTI or an RSN.
- We upgraded and patched our operating systems, software, and databases.
- We have begun developing a post processing and archival system that will be hosted in the Amazon Web Services cloud.
- As part of the AQMS effort to make AQMS code publicly accessible, we began transferring code base from the AQMS svn repository into a public GitLab repository. This included converting from svn to git, creating tutorials compatible with doxygen, and configuring the git repos so the documentation is included in the overall AQMS documentation.

Data Archiving

In FY 2019 We began storing a copy of the archive as an AWS Open Data Set. The waveform files are stored as channel day long in an AWS S3 bucket (https://registry.opendata.aws/southern-california-earthquakes/). Hosting the archive in this manner will allow users to access the data without having to download the enter dataset to their workstation. This is helpful for users working with large datasets, where retrieval of the data may require significant time and disk space before analysis. It will also give users greater access to computational tools available in AWS. Hosting our Recent Earthquakes Map in S3 has shown it to be an effective way to distribute data when there are spikes in demand. (Figure 10).



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Continuous Waveforms	0	0	0	0	0	0	0	0	0.102	0.383	0.52	0.593	0.678	0.74
Other Waveform Data											0.168	0.188	0.272	0.412
Triggered Waveforms	0.076	0.156	0.184	0.23	0.26	0.286	0.311	0.336	0.392	0.438	0.511	0.579	0.659	0.746

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Continuous Waveforms	0.996	0.963	1.881	4.789	14.4	23.52	29.41	36.71	44.89	54.1	67.45	83.72	95.21	105.7	116.3
Other Waveform Data	0.792	1.186	0.854	1.035	1.035	1.035	1.035	3	2.326	2.326	2.669	2.67	2.67	2.67	2.67
Triggered Waveforms	0.839	0.974	1.141	1.28	1.408	1.816	1.993	2.183	2.37	2.542	2.798	3.132	3.402	3.679	4.46

Figure 9. *Histogram showing the total size of the SCEDC triggered and continuous waveform archive since 1991.*

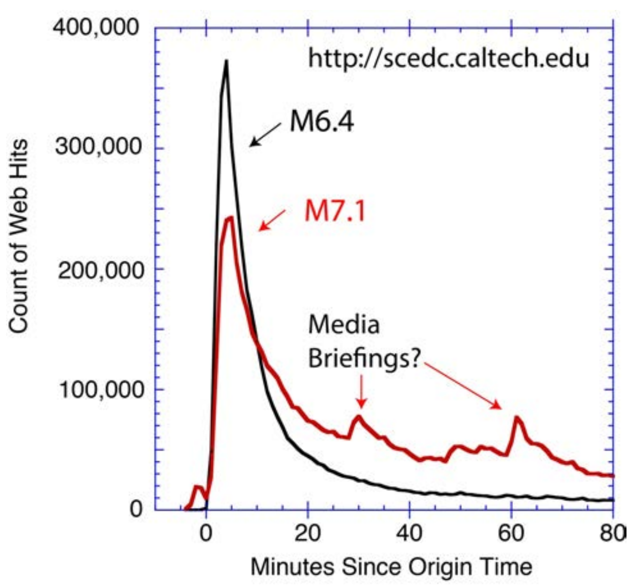


Figure 10. *Web traffic on the SCEDC website (http://scedc.caltech.edu) in one minute intervals following the M6.4 and M7.1 earthquakes, centered on the origin time. The peak of the distribution is reached within several minutes. The M7.1 had less web traffic than the M6.4 in part due to technical limitations; the later secondary peaks may be related to media briefings that took place at the Caltech Seismo Lab in Pasadena during a similar time period.*

Earthquake fault association

During 2018 and 2019, we have made progress on implementation of the earthquake association to a SCEC Community Fault Model (CFM) fault (Eq2CFM) method through the SCEDC, and developed a series of enhancements to the data products that are provided (common fault name associations, fault maps, links to fault attributes [e.g., through USGS Qfault database]).

The SCEDC is hosting this catalog locally and plans to submit this new catalog attribute to the ANSS ComCat national catalog. The SCEDC will also submit this product near-real time via email and post it to websites scedc.caltech.edu and NEIC to make it part of their earthquake.usgs.gov web pages and part of the ANSS ComCat (Evans et al., 2020).

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Caltech Supplement II: Station Information System (SIS) Development

Accomplishments:

- In FY2019 networks continued to add new stations and equipment into SIS. 18,346 pieces of field equipment are entered into SIS. 2,067 active sites are entered into SIS production. The network operators using SIS are Southern California Seismic Network (CI), Lamont Doherty (LD), CERI (AG, ET, NM), South Carolina Seismic Network (CO), CICESE (BC), the Hawaiian Volcano Observatory (HV), portions of the GS networks (operated by USGS Menlo Park and ASL), portions of Pacific Northwest Seismic Network (UW, UO, CC) and portions of the Northern California Seismic Network and Berkeley Digital Seismic Network (NC, BK) (Figure 11).
- During the 2019 Ridgecrest Sequence, the USGS was quickly able to distribute the metadata for aftershock deployments using SIS. This was critical in getting the GS aftershock data to be used in processing (for more details, also see Yu et al, 2017).
- We worked on behalf of these networks and with IRIS to ensure FDSN StationXML and dataless files produced by SIS could be used by IRIS software (IRIS FDSN web services). During the reporting period, SIS users used SIS to create FDSN StationXML files for stations 1,256 times.
- We have resolved any bugs and prioritized enhancement requests made by networks using SIS. We also handled new user requests, as well as general user inquiries. In the reporting period we have

fielded 96 such inquiries from the SIS user base and resolved 76 of them. Our change log can be found at this site:
https://wiki.anss-sis.scsn.org/SIStrack/wiki/SIS/UI/ChangeLog

- Throughout the year we have endeavored to keep documentation current in the SIS wiki. In FY2019 as a form of outreach to the user community, we began sending helpful tips to using SIS in the form of an email to the SIS listserv. We sent 4 such emails during the reporting period.
- We worked with NCSS and UW to prepare to load their metadata into SIS.
- To assist networks migrating into SIS, we enhanced the stationXML loader to accept load closed epochs into SIS.
- We also upgraded and patched our operating systems, software and databases. In FY 2019 we had a major database upgrade to Oracle 19c. We upgraded to Django 2.2 and python 3.7. We upgraded our java script libraries.
- To promote standardization of equipment templates, we introduced SIS standard templates that are curated by Patrick Bastien at ASL.
- We enhanced the usability of forms that create equipment and data stream templates.
- Users can now change logger templates on existing loggers.

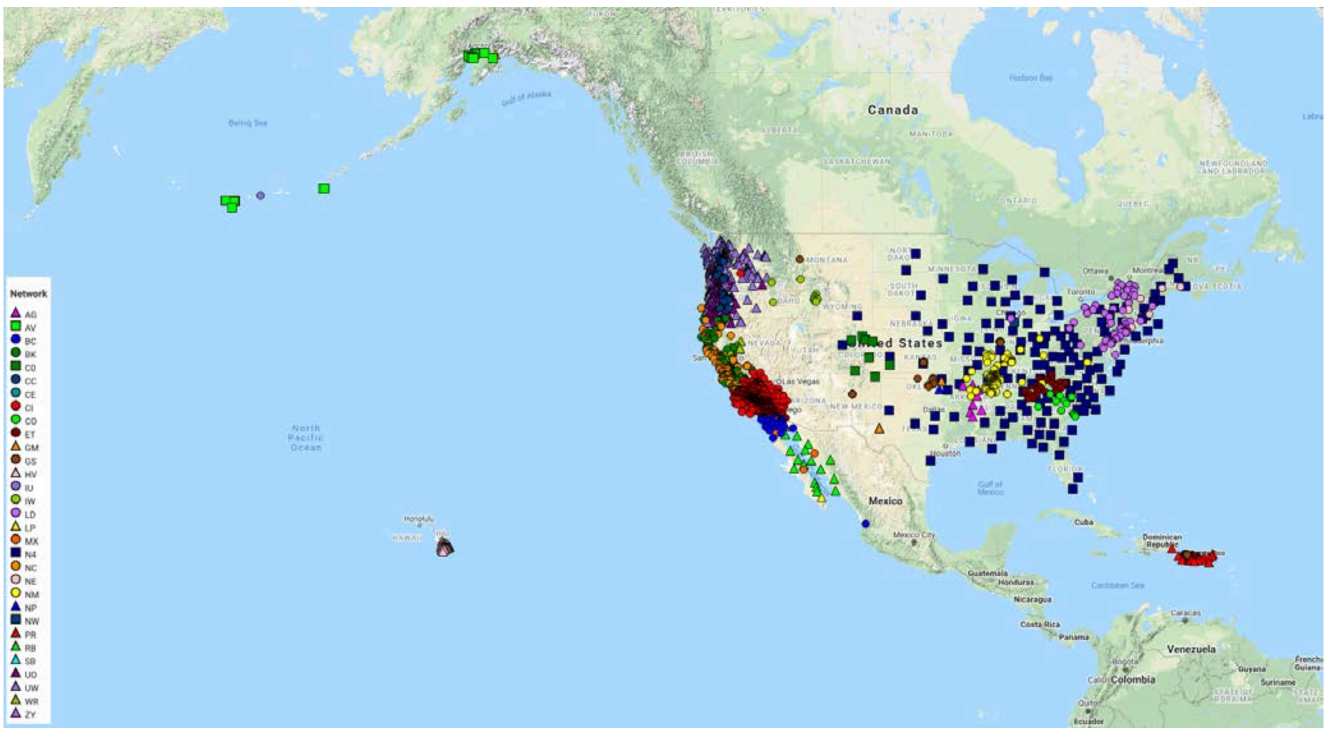

Figure 11. *Map of ANSS seismic stations routinely using SIS in production for metadata management.*

Anticipated Future Needs

- Reports for ANSS management (location of equipment, landowner by category, telemetry by category, station funding by category).
- Train users from CVO and other VHP networks to use SIS.
- Enhance GPS site description in SIS and allow users to write IGS logs from SIS.
- Support integrated logger-sensor packages to allow users to work more easily.
- Revise existing SIS equipment categories based on user feedback.
- Make the SIS installation more resilient by having a backup copy in cloud.

SIS Development Group

- Ellen Yu (Caltech) – technical lead and database administrator.
- Prabha Acharya (Caltech) – SIS developer, focusing on stored procedures.
- Sue Kientz (Caltech) – technical documentation and general support.
- Valerie Thomas (USGS) – TIC chairman.

Caltech Supplement II: AQMS Software Development

Background

The purpose of this work is to improve selected modules of the AQMS software used by the SCSN to acquire, process, and archive earthquake data. The software improvements will streamline the SCSN operations and make earthquake products more accurate. Because all AQMS software is shared amongst the ANSS funded regional networks, this effort will also greatly benefit them.

Below is a description of the four AQMS tasks Caltech is developing to improve AQMS reliability and operational capabilities and the work that was done during this period. The programmer tasks described are necessary to adapt these codes for use by the SCSN and other ANSS regional networks. We are using SCSN data flows to test and accelerate the development. We will post these codes on the new Github AQMS site and ask users to contribute new and better features or testing, which will lead to improved community code base. Below we discuss the status of four main tasks.

1. Station UI

Station UI is a web interface that allows the SCSN/AQMS operator to manage the database channel lists used by various AQMS applications. When station metadata is loaded into the AQMS database, an analyst must enter channels for that station into the database tables Applications and Appchannels for it to be used in real time and post processing applications. StationUI allows the analyst to do this without training in sqlplus or shell scripting. Station UI also has a rule set that allows users to enter a new station for multiple applications at one time, greatly simplifying the process. Station UI also allows querying of these tables so people can more easily understand what the current contents of a channel list are, rather than having them use sqlplus or viewing configuration files on servers.

Progress:

- In 2019 we modified the utility to make it more modular. This allows RSNs the option to integrate with other ticket systems or with CWB.

Remaining tasks:

- Add capabilities to enable users to craft their own rules for what channel lists are updated when a new station is entered
- Port to PostgreSQL database
- Upgrade to Django 3 and python 3
- Make the source code available in AQMS GitLab repository.

2. The wrapper scripts official name is 'dataless2aqms.py'

'dataless2aqms.py' is a wrapper script that calls the station metadata loaders Populate_RdSEED, SimpleResp and the Import_ExtStaXML.csh (developed at Berkeley). The main function of dataless2aqms.py is to streamline the process of loading station metadata into the AQMS IR and HT schemas. The wrapper script allows the AQMS operator to manage the loading of dataless files, whose locations may exist in different places. For example at SCSN, dataless file locations include SIS, IRIS, NCEDC and ANZA. The wrapper can also do automated loading with the SIS publish feed, where it detects an updated dataless and loads it into a staging environment. The wrapper script also automates any post loading steps, such as updating clipping information, and creating HAR files for full SEED generation. The wrapper script also can provide a verification step where it can diff the results from the staging database and the production database, allowing the operator to determine what differences will be seen when loaded into production.

Proposed improvements of the wrapper script would also help streamline adding new stations into AQMS processes. The following proposed work will be towards that goal:

Progress:

- In 2019 we modified the utility to make it more modular so users can use different metadata loaders. Users can specify different metadata loading tasks – such as whether to populating channel clipping values.
- Beta testing beginning at HVO
- Currently in development: allow users ability to configure and plug in their own bug tracking API.

Remaining tasks:

- Enhance new metadata detection – automate loading of metadata repositories in addition to SIS.
- Port to PostgreSQL database.
- Make source code available on GitLab.

3. Other projects that might benefit SCSN and other RSNs using CWB:

We also did development to enhance use of CWB by SCSN and other RSNs.

1. New development to improve the usability of the chkCWB script. chkCWB is a script to diagnose waveform completeness of newly acquired stations flowing into the CWB (Continuous Wave Buffer-developed at NEIC). Development would be to ensure it can be used by other RSNs using CWB (HVO, UU).
2. STP integration with CWB - work has been done at SCSN to have STP be able to query waveform data in CWB. Development would be to complete testing, security issues, as well as ensure it can be used by other RSNs using CWB (HVO, UU).

Progress

- chkcwb utility has been ported to python3.
- chkcwb code and its documentation has been released in Github for other RSNs and is in beta testing at HVO. (https://github.com/SCEDC/chkcwb).
- chkcwb installation and deployment uses python venv
- We have begun making python library for STP functionality. We have developed code to serve triggered waveforms as stream objects in ObsPy.
- Revised documentation for STP has been put on https://github.com/SCEDC/stp/wiki

Remaining Tasks

- Add to STP python library ability to write arrival phase objects in Obspy
- Release STP python library to GitHub
- Port STP to PostgreSQL

4. AQMS Testing System for SCSN: initial development

This task will enable a user to play back an event through a known version of AQMS code and configuration (configuration files, station metadata, station corrections). The testing mechanism will be through the Earthworm Tank file player as well as live data. We will also leverage the work already done by the EEW ShakeAlert T&C group.

This will allow the SCSN to evaluate the software and/or configuration by:

1. Examining the resulting products (i.e. origin, magnitude) of the playback
2. Comparing the resulting products with products from the playback of the same event, but different software and/or configuration version.
3. Comparing the results with production real time results.

Progress

- We identified the components that needed to be version controlled for playback.
- In 2019 we developed scripts to capture an image of a database configuration and deploy in a docker container.
- Archived data for playback, which contains information about when latent data became available for processing. This is necessary for faithful reproduction of results.

Remaining Tasks

- Script deployment of AQMS code and database configuration environment in a docker container
- Script comparison of playback with production data
- Software testing with playback of Ridgecrest sequence data.
- Deploy beta version of code to GitLab with documentation.
- Write a requirements document for future improvements for UI and use with L1Z data.